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DEVELOPMENT OF HTPB PROPELLANT SYSTEM FOR ISRO'S MOTORS

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Abstract

Reliable, efficient and cost effective propellant system has been developed and successfully static tested for use in the Polar Satellite Launch Vehicle (PSLV) of the Indian Space Programme. Though propellant formulations based on PBAN were available, a fresh choice of propellant system to power the solid stages of the PSLV had to be made considering the performance requirements of the motor, the mechanical and energetic properties of the propellant, the cost and availability of the propellant ingredients.

The functional requirements of the motors were as follows:

Parameters	PS-1	PS-3
Diameter, m	2.8	2.0
Length, m	20.35	3.5
Propellant weight, t	125.0	7.0
Action time, sec.	100.0	85.0

To enable the proper choice of the propellant a set of control studies were carried out to evaluate the mechanical properties, ballistics, aging and burn rate characteristics. The results of these along with the other factors yielded a higher weightage in favour of HTPB and further developmental work with this was undertaken.

One standard formulation was developed and scale up studies were undertaken. Burn rate requirements in the range of 8 to 10mm per second could be comfortably achieved by suitable adjustment of the burn rate accelerator percentage. To confirm the design approach and to get a handle on the process parameter control, sub-scale tests at one metre level were designed and carried out. These tests also gave insight into some practical problems. With the aid of these studies, full scale motors of both the first stage and third stage have been realised and static tested. The first stage motor is of segmented construction employing 5 segments of 2.8m dia each. Each segment contains approximately 25t of propellant. The third stage motor has a composite case of 2m diameter. The first stage motor employs SITVC system for steering and the third stage motor employs a flex nozzle control system. The basic design soundness and performance targets have been demonstrated in the tests.

Design and development features of the two motor systems are presented in the paper.

1. Introduction

The Indian Space Research Organisation (ISRO) has successfully developed and adopted composite propellants for its sounding rockets and the stage motors of satellite launch vehicles. Starting in the late 60's with free standing PVC plastisol propellants used in the sounding rockets, case bonded propellant system based on PBAN and CTPB type were used for the 4 stage motors of the country's first satellite launch vehicle, the SLV-3 and its augmented version, the ASLV.

The Polar Satellite Launch Vehicle was conceived in the early eighties. This 4 stage vehicle with a capability to place 1000kg payload in a 900km sun-synchronous polar orbit employs two solid propulsive stages. At this time, ISRO was developing composite propellants based on three binder systems, namely, poly-butadiene acrylic acid acrylonitrile (PBAN), ISRO Polyol Pedester (IPP) and Hydroxy terminated polybutadiene (HTPB). These had to be compared on a common scale in respect of the desired propellant properties and process parameters. Consequently, based on the mission requirements, the burn rate, energetic and mechanical property

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requirements were laid out and propellant formulations with the three systems to meet these common specifications were tried out.

Other aspects regarding processing, specifically, pot life and end-of-mix-viscosity as well as the viscosity build up rate were also important points for comparison and final choice of the binder system. Other allied aspects which were considered, included the availability of raw materials, ease of handling, toxicity aspects and long term storage and stability capability. Cost aspects were also taken into account but was not the overriding consideration.

Control studies for comparative evaluation of the three binder systems were carried out, followed by property tailoring, process scale up parameter adjustments, casting in sub-scale motors and testing. This was followed by the preparation and testing of the full scale stage motors.

2. Binder Choice

Like all general solid propellant binders, the three systems have chain extension and cross linking possibilities with suitable curators. They are also capable of being tailored over a range of properties.

2.1 Performance Goals

The propellant has to satisfy a set of requirements which sometimes appear to be contradictory. For example, there is a need for high solids loading with good mechanical properties and good processability. Good storage stability of the propellant and related components of liner and inhibition are also important considerations for evaluating the binder -propellant system. From the motor design, its service environs and practical considerations, the following performance goals could be set.

- Propellant density, kg/m^3	$1.78x10^3$
- B.R. at 6.9Mpa, mm/s	9.96
- Slope	0.4
- EOM vis., P	7000-10000
- Slurry pot life, hrs.	4.0

The binder should have stable storage properties.

The motor service life was to be 5 years under normal storage conditions. For the upper stage propellant, temperature cycling between 5 and 60 deg. C was a further requirement.

2.2 Binder description

As earlier stated the candidate binders were to be chosen from among PBAN, ISRO Polyol and HTPB. These binders and the status of propellant studies with them is described.

PBAN: PBAN is a terpolymer of butadiene, acrylonitrile and acrylic acid, and is characterised by the random attachment of both carboxyl and nitrile groups along the butadiene backbone. This polymer may be cured with a diepoxide/aziridine to yield a highly cross-linked network with a controllable molecular weight, by properly choosing curing agents ratios. The introduction of hydrogen bonding in PBAN improves its tear resistance but the propellant properties at low temperature tend to be poor.

The PBAN system had found extensive use in our motors since the early seventies and consequently, was the most familiar. Propellant based on this had been successfully used with upto 84% solids loading to power the first two stages of India's first satellite launch vehicle - the SLV 3. The propellant system had then been modified with increased aluminium content to obtain higher propellant density and higher specific impulse. Though the propellant consistently exhibited reproducible energetic properties, it was found to be rather sensitive to the curator purity and even when this was pegged at a high value the mechanical property reproducibility and the interface bond strength tended to be poor. Also the binder was not indigenously available and all the propellant manufacture was based on stocks procured from American Synthetic Rubber Company. Procurement and limited shelf life of the aziridine curator was also a problem.

IPP: This binder system was developed indigenously and belongs to the polyurethane family. ISRO polyol is a polyester and is produced by condensation polymerisation. THSA is dissolved in toluene and allowed to self polymerise in the presence of a catalyst. At a specified stage of polymerisation, the modifier TMP is added to increase functionality. Final product is obtained by distillation under vacuum. The functional hydroxyl groups are secondary and the cross-link reaction rate with the curator iso-cyanate (TDI) is slow compared to that for HTPB prepolymer. To accelerate the cross-linking reaction and, at the same time, to preclude side reactions, the curing temperature is set at 60 deg.C. The ester group in the polymer backbone has a tendency to lower the energetics. Propellant based on this binder has found applications in sounding rockets. Though the required mechanical properties could be achieved, there was lack of repeatability of the cure reactions and the achieved end properties.

HTPB: The HTPB binder is a telechelic polymer, i.e. a hydroxyl group is present at each end of the macromolecular chain. Basic propellant formulation studies with ARCO-R-45 resin had shown promising results. Subsequently the binder had been indigenously developed and scaled up using the free radical process and propellant formulation trials had yielded satisfactory results in respect of both mechanical and energetic properties.

The basic specifications of the three binder systems are compared in table 1.

Table 1: Basic specifications of the binder systems

Property	PBAN	IPP	HTPB
1. Specific Gravity	0.94	0.93	0.91
2. Viscosity at 30degree C,CP	3500 to 4000	1800 to 2800	4000 to 6500
3. Hydroxyl value, mg KOH/gm	-	45-55	40-50
Carboxyl value mg KOH/gm	33-39	-	-
4. Acid value mg KOH/gm	0.65	1.5	1.0
5. Volatile matter (max), %	0.75	1.0	0.5
6. Moisture content (max), %	0.2	0.1	0.1

2.3 Propellant Property Goals

The binder and propellant system were required for ISRO's Polar Satellite Launch Vehicle (PSLV) which is being developed to place a 1000kg payload in a 900km sun-synchronous polar orbit. The vehicle has four main propulsive stages of which the booster and the 3rd stage are solid stages. In addition, there are six 1m diameter strap-on motors which burn concurrently with the first stage booster. The first stage booster is of 2.8m diameter 125t of solid propellant contained in 5 segments while the third stage motor is designed with 7t of propellant in a 2m diameter composite chamber. The propellant system called for a high degree of reliability and repeatbility.

A propellant system based on maximum commonality of elements for application in both stages was the requirement. From the propellant performance and service goals the following requirement were generated:

BR, mm/sec at 6.9MPa	8.5 - 9.8
Std. Isp, sec.	244
Density kg/m^3	1.77-1.79x10^3
Tensile strength, MPa	0.74
% elongation	35
Initial modulus,MPa	2.94-4.9
Service temperature requirements (C.degrees)	+5 to +40
Storage life (min.)	5 years

The basic propellant formulation should cater to both the stage requirements and the burn rate should be adjustable with suitable modifiers.

Liner system should be common for both the motors and should be compatible with both nitrile and EPDM based insulation system.

2.4 Development Studies

Propellant formulation and evaluation studies were undertaken with the three binder systems. The processability was also a main factor for consideration and evaluation. The burn rate requirement was not given undue importance at this stage except what could be achieved with the adjustment of coarse to fine ratio of the AP. Any residual requirement, it was argued could be made up by incorporation of a suitable modifier.

The steps in the basic comparison studies included:

a) Formulation in 4kg carton level - assessment of properties and adjustment.

b) Mixing at 120kg level casting of control rounds to evaluate properties and ballistics.

c) Scale up in 1 tonne sigma mixer and casting and testing in control rounds.

The control rounds are nominal 40kg charges of 200mm diameter and 1m long tested in heavy wall casing.

The summary comparison of the evaluation studies is shown in table 2.

Table 2: Comparison of slurry and propellant properties

Parameter	PBAN	IPP	HTPB
EOM Vis., at 40 deg. C,P	5120	6400	9000
Build up after 3hrs. at 40deg.C,P	6700	14700	13000
Tensile strength, MPa	0.45-0.7	0.34-0.5	0.75-0.86
% elongation	22-34	33-44	35-41
Initial modulus, MPa	2.3to 4.8	1.5to 2.6	3.5to 5.0
Density, $kg/m^3 x10^3$	1.78	1.78	1.78
Burn rate at 6.9MPa, mm/sec.	10.72	9.53	8.2
Std Isp, sec.	243	241	246

From the above comparison, it could be seen that:

i) The unloading viscosity and the viscosity build up rate in the case of HTPB was higher than that of the PBAN and IPP systems. However, this was not considered a worrisome feature as vacuum casting up to levels of 15000 cps was not expected to be a problem.

ii) The properties in respect of density, Isp and, burn rate were comparable.

iii) The mechanical properties met the requirements only in respect of the HTPB systems.

Besides the above parameters, other aspects of binder availability, and cost were considered.

PBAN scored the lowest weightage as:

* PBAN and its curator system was not readily available indigenously and indigenising the process and industrial scale up would take considerable time.

* Because of the above factor, its cost was also on the high side.

IPP binder and HTPB were comparable as they had been indigenously developed and the IPP system had been licensed to industry also. Licensing the industry to take up HTPB was also found feasible.

In terms of cost the IPP binder was found to be the cheapest, followed by HTPB and PBAN. The cost of the three binder systems respectively were in the ratio 1:2:4.

Though, in terms of cost and processing, IPP displayed some advantages over the HTPB system, it had a major handicap of providing mechanical properties below specifications and also of large scatter in the properties in the sounding rocket applications. Consequently, the HTPB system was chosen for further developmental studies and applications. The choice was also in line with the international trend, where a positive preference for using HTPB as the workhorse propellant binder was becoming evident.

3. HTPB Binder & Propellant Development

3.1 Binder Development

The development and production of the binder was taken up using the free radical process and using the batch process shown in fig.1. The basic process was initially developed at a lab scale of 2kg/batch from which it was scaled up. As a first step, the process was scaled up in a 200 litre pressure reactor to a level of about 35kg of resin per batch. The process was standardized over a number of batches to reproducibly obtain the resin properties as also downstream properties in the propellant. Based on the successful outcome of this further augmentation inhouse and in industry was taken up and using a 1000 litre capacity pressure reactor a capability to produce 180kg of resin per batch was achieved. Sufficient trial runs were made at this level also for finetuning and freezing the process parameters. The individual batches were also blended into larger lots to balance out minor batch to batch dispersion and to ensure the blended mix falls within the specification band. The properties achieved are compared with ARCO R-45 HTPB property range in table 3. In the final analysis, the yield of resin obtained was 95%. Also detailed storage, sample drawal and testing programme has shown no deterioration of the resin properties with time.

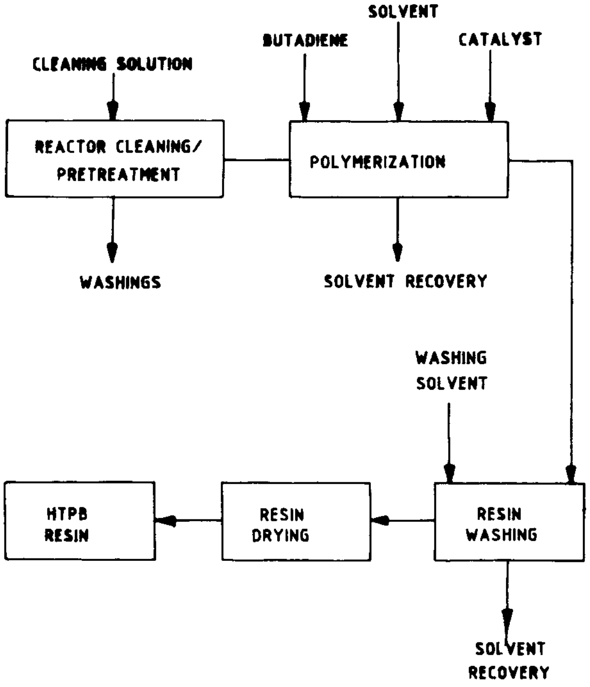


Fig.1 - Process Diagram of HTPB Binder

Table 3: Performance criteria

Item	Arco catalogue for R45 typical values	ISRO HTPB
Hydroxyl value mg of KOH/gm	42.1	45.2(Mean) (=2.6)
Average molecular weight	2800	2470(Mean) (=140)
Functionality, -Fn	2.1	2.01 (=0.165)
Viscosity CP at 30degree C.	5000	5195(Mean) (=706)

3.2 Propellant Development

Having decided on the binder, the effort now was to tailor the propellant to meet all the required attributes in terms of the specified properties, processability and aging.

The primary formulation evolved employed TMP as the crosslinking agent. The burn rate could be adjusted over the 8-10mm/sec range by using iron oxide as burn rate modifier. The modifier percentage was varied upto 0.5% to obtain the desired burn rate. The propellant development followed the following sequence:

Mix size	Objectives
a) 4kg	- Propellant tailoring to meet specified property goals.
b) 60kg	- Confirmation by casting and testing of control round.
c) 650kg	- Scale up in 1 t sigma mixer.
	- Process parameters fixing.
	- Determination of burn rate law.

d) 2.5t - Scale up in planetary mixer.

- Finalization of ingredient addition, and mixing sequence/parameters and cast/cure conditions.
- Determination of scaling effects on mechanical properties.
- Process certification.

It was found that the required energetics and mechanical properties could be met with a 86% solids loading formulation containing 18% aluminium.

For scaling, the well known similarity principles were employed for fixing the RPM of the vertical mixer and a mixing time of 180 minutes was found to be sufficient for getting a well blended slurry. The blending was further confirmed by carrying out trace analysis of the slurry.

3.3 Development Problems & Remedies

During the development and scale up problems were encountered and were resolved. Some of the major problems are listed.

* Uniform dispersion of TMP in the slurry was found to be problem as its temperature had to be accurately controlled. Otherwise the TMP had a tendency to crystallize on the feed chute walls.

* Reaction exothermicity after curator addition. The change can jacket water temperature had an important influence on EOM viscosity and viscosity build up rates.

* Partly due to the above reason there was rather wide and unacceptable dispersion in the EOM viscosity values. The EOM viscosities in the planetary mixer were normally high.

Also at this stage difficulty was experienced in improving the elongation properties. Survey pointed to TMP as the possible culprit for both the elongation and the EOM viscosity. Being trifunctional, its cross linking density is very sensitive to the binder resin properties. The remedy lay in the introduction of a suitable low molecular weight chain extender in the formulation. Incorporation of 1,2 butanediol along with TMP solved the problem of both mechanical properties, the EOM viscosity and repeatability of data. Also by dissolving the TMP in butanediol, the problem of dispersing the TMP uniformly during the mixing process could be fully overcome.

Typical properties now being achieved in the 2.5 tonnes mix are tabulated below:

Table 4: Typical properties in 2.5t mix

a)	EOM viscosity at 40 deg.C., P	6500-8000
b)	3 hr build up, at 40 deg.C, P	12000-14000
c)	Density, kg/m^3	$1.77x10^3$
d)	TS, MPa	0.7 - 1.0
e)	% E	35 - 45
f)	Modulus,MPa	2.5 - 5.0

3.4 Burn Rate Adjustments

To get the required burn rate, an accelerator had to be incorporated. Iron oxide gave some augmentation, but was below the requirement. The acceleration content did not have significant bearing on the burn rate increase . The required enhancement could, however, be obtained by using copper chromite as the accelerator. The burn rate enhancement with accelerator quantity is shown in fig.2.

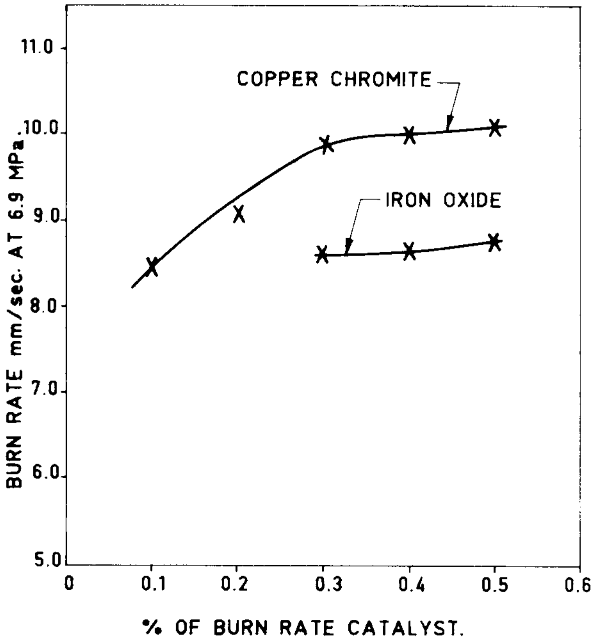


Fig.2 - Effect of Catalyst on the Burn Rate of Propellant

4. Interface systems

Along with the development of the propellant, the development of liner and an inhibition system were also undertaken. The liner systems already in use with the PBAN system had shown some proneness to interface defects. It was also felt that a fully cured liner system should be developed to remove any element of subjectivity in its application and use. From the process angle, the liner was required to have a consistency which would enable its spraying on to the insulation surface. Obviously, the liner had to perform the main function of providing a defect-free bond at the insulation/ liner/propellant interface and prevent the migration of any species from the propellant. With these objectives in view a liner system based on HTPB binder, fully curable at ambient temperatures (25-35 degrees C) was developed. The system could be sprayed on to the abraded and preheated insulation in two coats. The properties of the liner are shown in table 5.

Table 5: Properties of the liner

a)	TS, MPa	2.0 - 3.0
b)	% Elongation	150 - 180
c)	Initial modulus,MPa (stress at 100% elongation)	1.0-2.0
d)	Hardness, Shore A	55 - 65
e)	Density, (kg/m^3)x10^3	0.99-1.01
f)	Peel strength (kg/m)x10^2	0.6-1.4
g)	Tensile bond strength, MPa	0.6-0.9

As there was a large experience with the nitrile insulation and as this system was well characterized it was adopted for the motors. The thermal and mechanical properties of the insulation are shown in table 6.

Table 6: Properties of insulation system

a)	TS, MPa	15 - 30
b)	% Elongation	800 - 1200
c)	Hardness, Shore A	60 - 75
d)	Density, (kg/m^3)x10^3	1.18-1.20
e)	Peel strength (kg/m)x10^2	
	Case/Rubber	4.5 - 8.0
	Rubber/Rubber	4.0 - 6.0
	Rubber/Propellant (with liner)	0.6 - 1.4
f)	Specific heat (J/kgK)x10^3	1.47-2.10
g)	Thermal conductivity (W/mK)	0.21-0.25
h)	Co-efficient of liner thermal expansion(1/K)x10^{-4}	1.5-2.0
i)	Erosion rate (m/s)x10^{-3}	0.16-0.20

For a potential upper-stage application, an insulation system based on EPDM was also developed. To obtain low density, cork filler was employed. Initial trials showed density in the range of $0.8\text{-}1.0\times10^{3}$ Kg/m^{3} with erosion rates of 0.12 to 0.15mm/sec. The system was not employed in the upper stage motor as the time frame of development, characterization and scale-up and moulding of this insulation were not compatible with the motor readiness requirements.

The fore and aft faces of the booster propellant segment by design require to be inhibited. Here a system based on polyurethane with which satisfactory experience existed was employed. The inhibition and interface properties are shown in table 7.

Table 7: Properties of inhibition system

a)	TS, MPa	0.9 - 1.4
b)	% Elongation	30 - 35
c)	Hardness, Shore A	60 - 70
d)	Density, (kg/m^{3})x10^{3}	1.14-1.22
e)	Peel strength (kg/m)x10^{2}	0.6-1.0
f)	Tensile bond strength, MPa	0.7-0.9
g)	Sp. heat (J/kgK)x10^{3}	1.47-2.10
h)	Thermal conductivity(W/mK)	0.25-0.29

5. Mechanical Property Correlations and Aging Trends

Mechanical property correlation between the carton and main propellant grain was established by measuring property from dissected large size propellant grains. The large size castings exclusively undertaken for such studies comprised two 800mm dia, 1 t propellant blocks, and one 2m dia, 9 t ropellant block. Details are indicated in table 8.

Table 8: Properties of scale up

Parameter	Grain diameter in mm		
	800-1	800-2	2000
Tensile Strength:(MPa)			
Carton	0.75	0.72	0.68
Main Grain	0.85	0.78	0.79
Main/Carton ratio	1.13	1.08	1.16
Elongation: (%)			
Carton	34.5	33.0	36.83
Main /grain	29.0	30.0	23.44
Main/Carton ratio	0.85	0.93	0.64
Modulus: (MPa)			
Carton	5.1	4.3	3.96
Main Grain	6.5	5.68	6.85
Main/Carton ratio	1.27	1.32	1.73

The average values of the main grain to carton ratio were used for design and structural analysis of the propellant system.

It was required that the main components as well as the propellant show long range stability of properties with low degradation rates.

Detailed studies have been carried out on the aging trends of the HTPB binder and the propellant system. The HTPB binder has shown good stability of properties over a 15 month period of quarterly monitoring of the properties. Only a slight increase in the viscosity value, though within the specification band, is discernible.

Actual aging data on the propellant and interface properties is limited. However, using this limited data of natural aging of the propellant samples over a period of one year and using the well known aging model:

$$P = A \log [t/t_o] + P_o$$

where P = aged property
A = aging rate constant
t = age time
t_o = initial time at which property P_o is determined

the aging rate constant A has been evaluated for different properties and subsequently for computing the aged property. The extrapolation shows no adverse loss of structural margin in terms of propellant mechanical properties upto 5 years. The model also depicts a continuous drop in the tensile bond strength of the insulation/liner/propellant interfaces without any significant change in the peel strength.

The aging trend is depicted in fig.3. The trend and the data will be confirmed through further evaluation of aged samples.

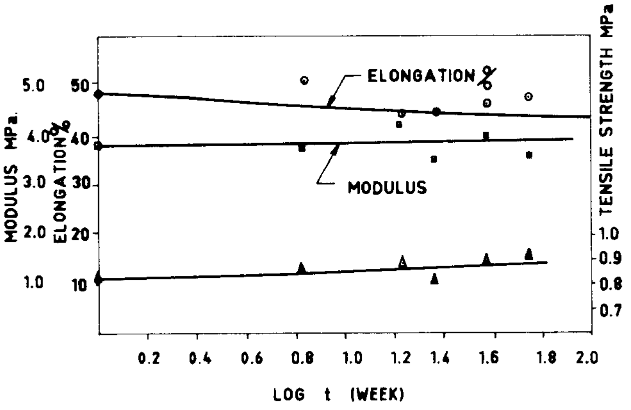


Fig.3 - Aging Trend of HTPB Propellant

6. Development of the motors

The development of the propellant and allied systems were tried out on sub-scale motors comprising a 800mm diameter 1.1 t motor and 1m dia, 8.5t motor. Propellant process parameters, propellant properties, interface integrity, cure shrinkage data and ballistics were evaluated. Certain aspects of the booster motor segment joint were also simulated in the 1m test. Subsequent to this the full scale motors were taken up.

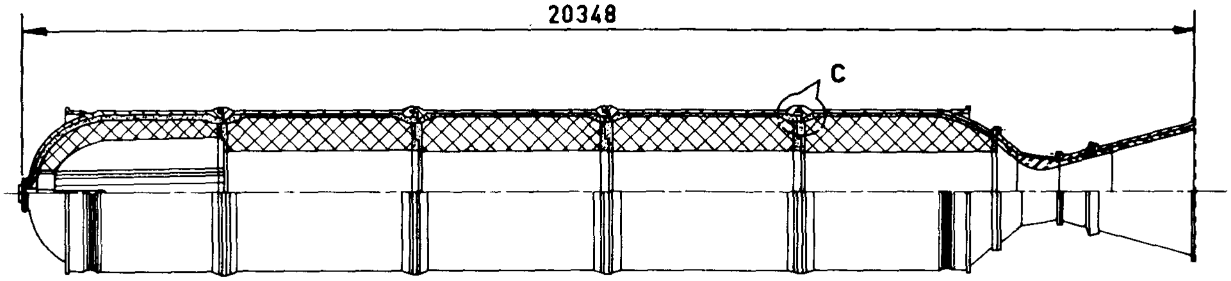
6.1 PS-1 Motor

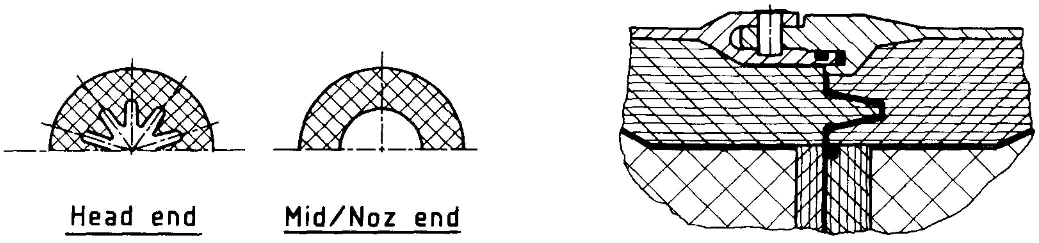
This booster provides the main lift off thrust to the vehicle and along with the aid of the strap-ons lifts the vehicle to an altitude of 57km, imparting to it a velocity of two Km. per second. The motor contains 125t of HTPB propellant providing a take off thrust of 360tonnes. The stage nozzle is equipped with Secondary Injection Thrust Vector System for providing control in the pitch and yaw directions. Roll control is separately provided by RCS thrusters.

The booster is constructed in 5 segments each of nominal diameter of 2.8m and height of 3.4m. Each segment is separately insulated, cast with propellant and assembled and held together at the tongue and groove joint by means of pins. The centre segments are interchangeable as they are identical in all respects. The rocket exhaust gases are led out through a conventional convergent-divergent nozzle with carbon and silica thermal protection systems. Ignition is achieved by means of pyrogen igniter located at the head end of the motor.

The head end of the grain has a deep fin configuration, essentially designed to provide high initial burning surface to obtain the required take-off thrust. The entire propellant in the segment is consumed in the initial 15 - 20 seconds. The remaining segments all have centre perforated grain configuration and contain approximately 25 to 28t of propellant.

The chamber is insulated from the propellant hot gases by a nitrile rubber insulation of the same type as employed for the smaller motors described earlier. The insulation procured in unvulcanised sheets is laid into cleaned and prepared motor chamber, built to the required thickness and cured in an autoclave. The end faces of the insulation are machined to provide a reverse tongue and groove configuration. A coating of the liner is applied on the insulation prior to propellant casting under vacuum. After curing the ends of the grain are inhibited and made to butt against each other during assembly. The space between the machined insulation faces is filled with a silicone potting compound and acts as a thermal barrier. The details of the motor and its performance are shown in fig.4.

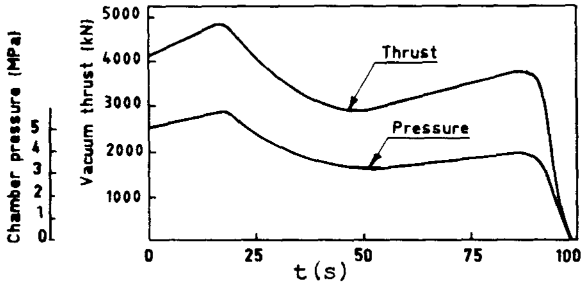




Propellant section

Segment joint detail 'C'

Performance curve



Performance.

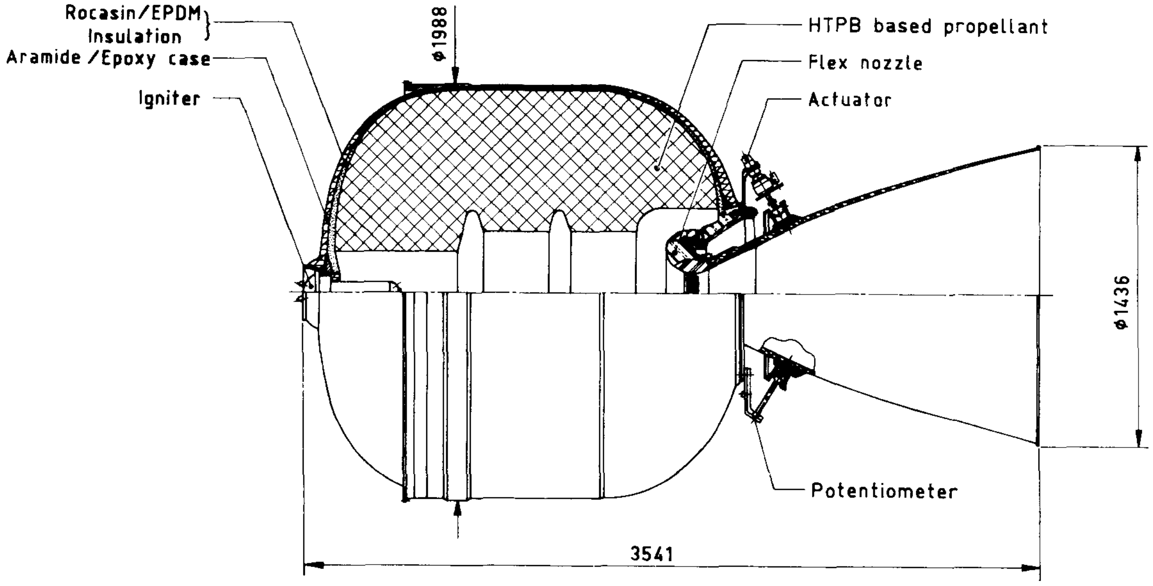
Outside diameter	m	2.804
Propellant weight	t	127
Motor mass ratio (min)		0.873
Design MEOP	MPa	5.88
Action time vac. Isp. (min)	Ns/kg (s)	2570 262
Action time	(s)	100
Max. thrust in vacuum	kN	4860

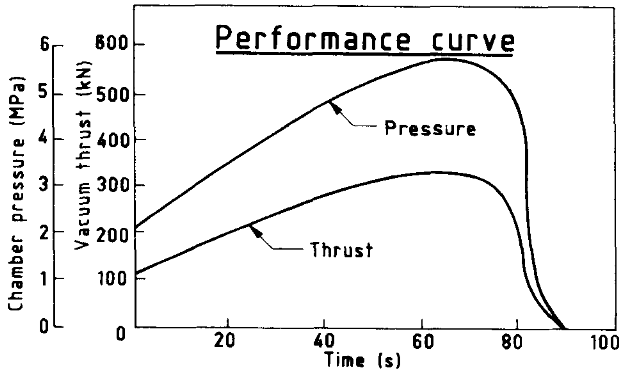
Fig.4 - PS 1 Motor

6.2 PS-3 Motor

This is a high performance motor designed to achieve a propellant fraction of 0.915. The motor has a diameter of 2m and is equipped with flex bearing system for thrust vector control. The motor design provides option for off loading the propellant. The case is of aramide/epoxy filament wound construction for the shell and carbon/aramide/epoxy hybrid lay up construction for the skirt extension at head end. The basic propellant composition is the same as used for the first stage except that the burn rate is derated by adjustments in the burn rate modifier content. The propellant grain port is of slotted configuration to maximise the propellant loading. The grain geometry is derived by initially casting with a cylindrical mandrel and subsequently machining to the required configuration. The grain also offers offload capabilities. The insulation system employed is based on nitrile rubber with silica filler. The details of the motor and its performance are shown in fig. 5.

Both motors have been successfully static tested and further qualification tests are in progress.





Design parameter

Outside diameter	m	1.988
Propellant weight	t	7.297
Motor mass ratio	-	0.915
Design MEOP	MPa	6.37
Action time Vac. Isp	Ns/kg	2857.7
Action time	s	85.75
Max. thrust in vacuum	kN	328.7

Fig.5 - PS 3 Motor

7. Conclusion

The development and characterization of the HTPB propellant has been satisfactorily completed and the system has been very successfully incorporated and demonstrated in the PSLV stage motors. These motors, as of now are the largest of their kind outside the USA. Change over to the HTPB system for the other motors of ISRO is also being implemented and a reduced burn rate formulation has been developed for these applications.

8. Acknowledgement

The development reported here is the outcome of the efforts of a large number of colleagues in ISRO's two major Centres - the Vikram Sarabhai Space Centre and the SHAR Centre. Their contributions to the successful development reported in this paper are too numerous to individually acknowledge. The authors consider it a great privilege to have worked with them and catalysed the successful development.